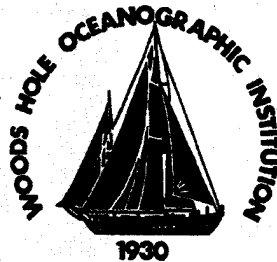


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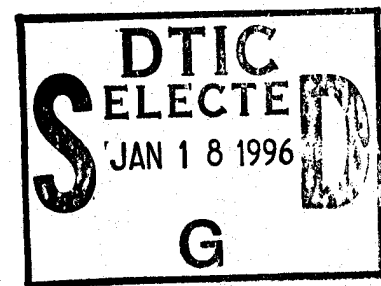


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Technical Report

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George V. Frisk, Chair
Department of Applied Ocean Physics and Engineering

DESIGN CONSIDERATIONS FOR STRETCH CONDUCTORS IN OCEANOGRAPHIC MOORINGS

1.0 INTRODUCTION

Telemetry communication with submerged sensors in oceanographic surface buoy moorings allows real time monitoring of sensor output from a land based station. This telemetry capability requires the presence of a reliable conductor path between submerged sensors and the surface buoy. Up to now a conductor path inside a stretching nylon mooring rope was not considered feasible. Nylon rope under service loads elongates up to about 20 percent. A copper conductor will suffer early fatigue failure when its ½ percent elastic elongation is exceeded. This report summarizes the design procedure to allow a copper conductor assembly to stretch 20 percent without elongation of its copper wires. Such a compliant conductor can form the electrical core of a nylon braided rope. A prototype conductor assembly is also described.

2.0 DESIGN PROCEDURE FOR A STRETCH CONDUCTOR

The insulated copper conductor has to be arranged to allow at least 20 percent elastic elongation of its assembly in order to serve as electrical core of a nylon rope. This can best be achieved by spiraling the conductor into a tight helix similar to the configuration of a telephone cord. Since stretching a coiled conductor requires substantially less force than stretching of the copper conductor itself, the spiraled conductor will respond to applied elongation by stretching its helical geometry, not by elongating the copper conductor.

In order to not collapse the helical conductor configuration inside a nylon braided rope under tension, the insulated copper wire must be spiraled around a stretchy core. The stretchy core will respond to an applied tension with axial elongation and the contraction of its diameter. The larger the radial contraction of the core at a given elongation, the easier it is for a helical wrapped conductor to stretch its geometry.

If the core would not contract when stretching, the helical wrapped conductor could only stretch by elongating the conductor itself. Such a behavior would be unlikely, since it would actually increase the volume of the elongating core. Almost all materials except reentrant foams and cork (1) contract under strain. The degree of contraction is characterized by the Poisson ratio μ , which is the ratio of lateral contraction and axial elongation, or

$$\mu = \frac{(d_{ro} - d_r)/d_{ro}}{(l - l_o)/l_o} \quad (1)$$

where: d_r is the core diameter, and
 l is an assumed length of core material.
the subscript $_o$ is the dimension at zero stretch

2.1 Geometry of Relaxed and Stretched Conductor Assembly

A view of the relaxed and stretched conductor assembly is shown in Figure 1.

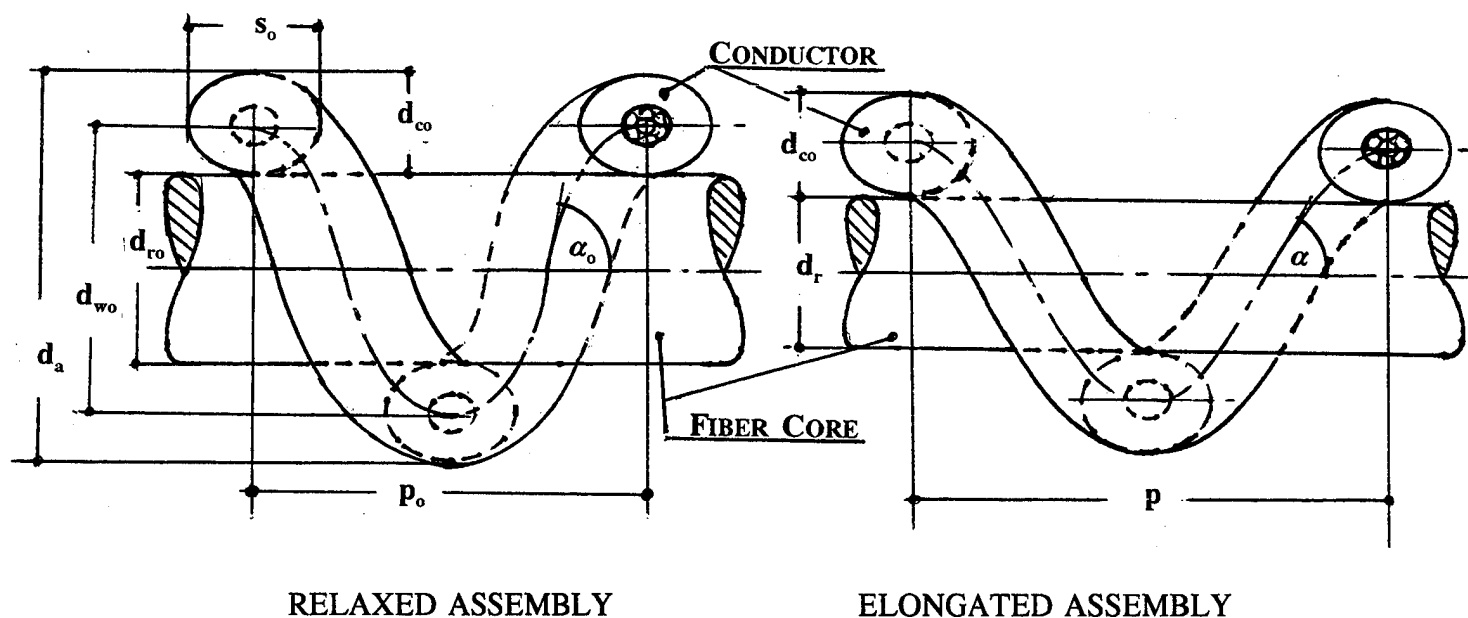


Figure 1: Sideview of Stretch Conductor Assembly

Legend:

- d_{co} diameter of insulated conductor
- l_{co} length of conductor axis
- d_r diameter of center core
- d_w wrap diameter of conductor = $d_r + d_c$
- d_a outer diameter of cable assembly
- α wrap or helix angle between conductor and cable core axis
- p pitch length of one conductor wrap
- s projection of spiraled conductor parallel to cable axis

The subscript _o indicates unstretched (relaxed) condition. Lack of subscript indicates stretched dimension.

2.2 Determination of the Conductor Wrap Angle

The following ratios are introduced, assuming no stretch of the copper conductor:

$$\tau_a = \frac{\text{stretched conductor assembly length}}{\text{relaxed conductor assembly length}} = \frac{p}{p_o} \quad (2)$$

$$\tau_d = \frac{\text{contracted diameter of center core}}{\text{relaxed diameter of center core}} = \frac{d_r}{d_{ro}} \quad (3)$$

$$k = \frac{\text{conductor diameter}}{\text{relaxed center core diameter}} = \frac{d_{co}}{d_{ro}} \quad (4)$$

The helical conductor path, rolled out on a plane, is shown in Figure 2.

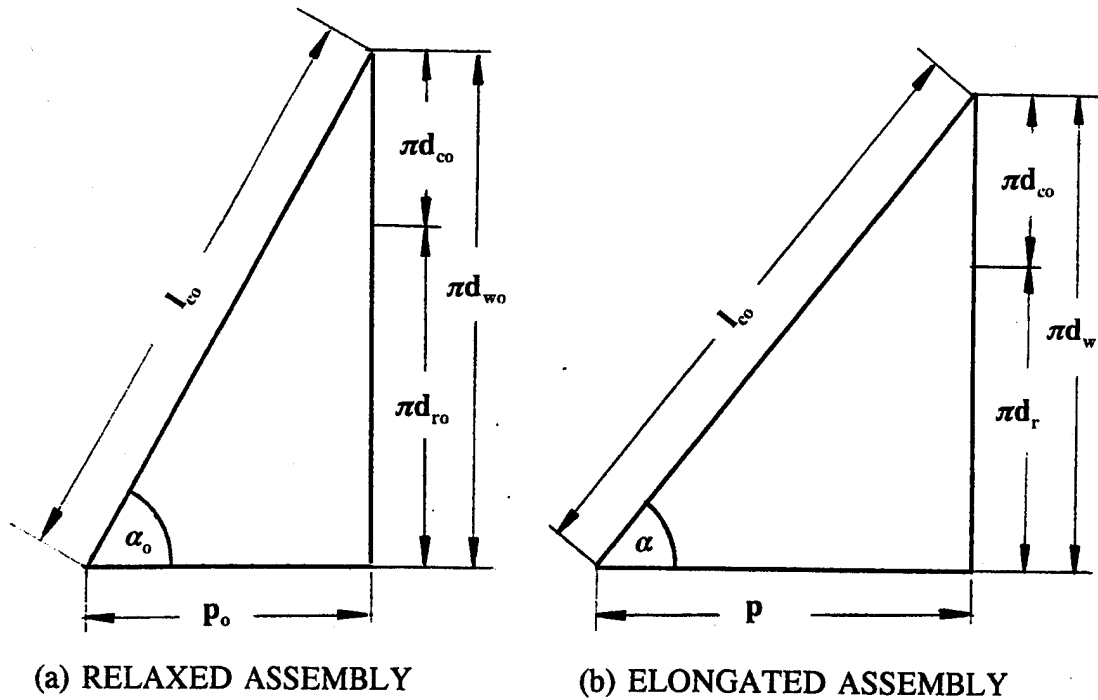


Figure 2: Helical Conductor Path in Cable Assembly, Rolled out on a Plane.

From Figure 2 we obtain using ratios (2) and (4):

$$\frac{\sin \alpha}{\sin \alpha_o} = \frac{(d_{co} + d_r) l_{co}}{(d_{co} + d_{ro}) l_{co}} = \frac{k + \tau_d}{k + 1} \quad (5)$$

$$\frac{\cos \alpha}{\cos \alpha_o} = \frac{p l_{co}}{p_o l_{co}} = \tau_a \quad (6)$$

$$\text{with } \sin \alpha = (1 - \cos^2 \alpha)^{1/2} = (1 - \tau_a^2 \cos^2 \alpha_o)^{1/2} \quad (7)$$

Combining Eqn. (7) and (5) yields

$$\cos^2 \alpha_o = \frac{2 k (1 - \tau_d) + 1 - \tau_d^2}{\tau_a^2 (1 + k)^2 - (\tau_d + k)^2} \quad (8)$$

Combining the Poisson ratio (Eqn. (1)) with Eqn. (2) and (3) gives:

$$\tau_d = 1 - \mu (\tau_a - 1) = (1 - \mu \epsilon_a) \quad (9)$$

where ϵ_a is the strain of the conductor assembly

Substituting τ_d in Eqn. (8) gives:

$$\cos^2 \alpha_o = \frac{1 + 2 k - (1 - \mu \epsilon_a)^2 - 2 k (1 - \mu \epsilon_a)}{\tau_a^2 (1 + k)^2 - (1 - \mu \epsilon_a + k)^2} \quad (10)$$

Eqn. (10) computes the conductor wrap angle α_o around a fiber core with the following input: Conductor and fiber core diameter d_{co} and d_{ro} ($k = d_{co}/d_{ro}$), Poisson ratio of the central fiber core μ , and required stretch of assembly $\epsilon_a = \tau_a - 1$. The computed wrap angle will leave the conductor unstretched. Results of Eqn. (10) are shown in Figure 3.

Figure 3 shows that with growing fiber core diameter (= decreasing k) and growing Poisson ratio the conductor wrap angle decreases. However with increased elongation requirement of the conductor assembly the wrap angle must be increased as well.

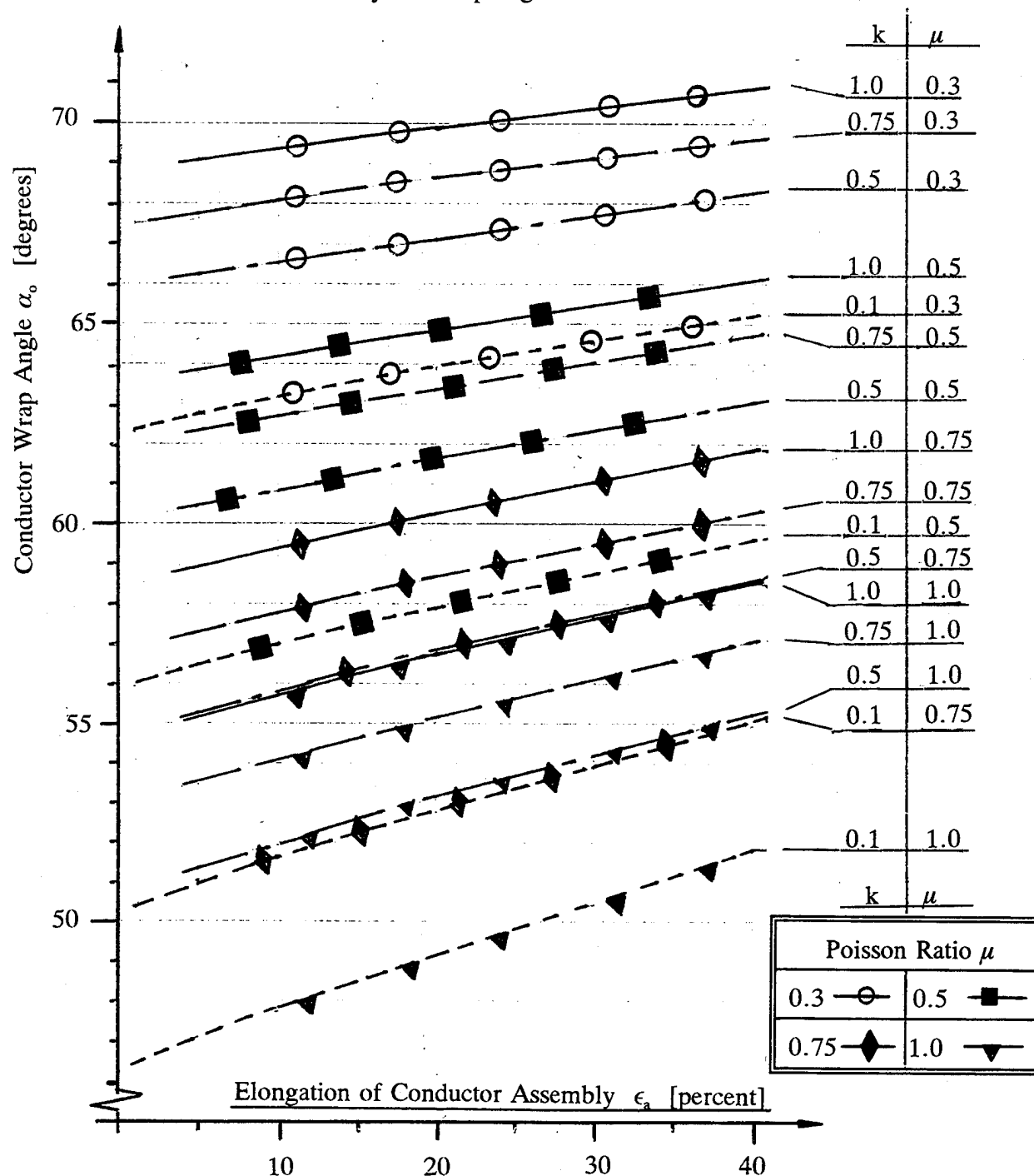


Figure 3: No-Stretch Wrap Angle for Conductor Vs. Required Elongation of Conductor Assembly as Function of Assembly Geometry and the Core Poisson Ratio.

2.3 Space Limits

The maximum coil angle α_o is reached, when adjacent conductors touch. This condition is reached for a single conductor when $s_o = p_o$, see Figure 1. The projection s_o of the conductor parallel to the cable axis is $d_{co}/\sin \alpha_o$, assuming a circular conductor cross section.

$$\text{It is also: } \tan \alpha_{o \max} = \pi d_{wo}/p_{o \min} = \pi (d_{ro} + d_{co}) \sin \alpha_o d_{co}^{-1} \quad (11)$$

With $d_{ro} = d_{co} / k$:

$$\cos \alpha_{o \max} = [\pi (1 + 1/k)]^{-1} \quad (12)$$

If more than one conductor is wrapped as a layer parallel around the fiber core, Eqn. (12) changes to:

$$\cos \alpha_{o \max} = n [\pi (1 + 1/k)]^{-1} \quad (13)$$

where n is the number of conductors. With increasing number of conductors and larger values for k the wrap angle $\alpha_{o \max}$ decreases rapidly, e.g. for $k = 0.75$ and 5 conductors $\alpha_{o \max}$ is 47° , for two conductors the maximum wrap angle is 74° .

2.4 Layer Blockage

The maximum wrap angle determined in Eqn. (11) and (12) would create a tight wrap of conductors, the wires are spiraled shoulder to shoulder with no space inbetween. This will result in a stiff, inflexible assembly, in which the conductors block each other. In order to avoid "layer blockage", extra space has to be provided. The additional space will allow contraction of the space for the spiraled conductor(s) on the inside of a bent configuration.

The amount of extra space depends on the smallest diameter over which the cable assembly has to be bent. This bend diameter is influenced by the size of the nylon rope which will cover the stretch conductor. The smallest rope bend diameter is typically one half to one times the rope diameter, and the conductor assembly should easily allow such a rope bend.

Figure 4 shows a rope with a conductor assembly core bent over a diameter d_b . It is

d_n = bend diameter of the neutral axis of the rope and conductor assembly, the neutral axis is assumed to be the rope axis.

d_{of} = bend diameter of outer, stretched conductor layer

d_{ic} = bend diameter of inner, compressed conductor layer

d_{wo} = wrap diameter of conductor around fiber core = $d_{co} + d_{ro}$

d_m = mooring rope diameter

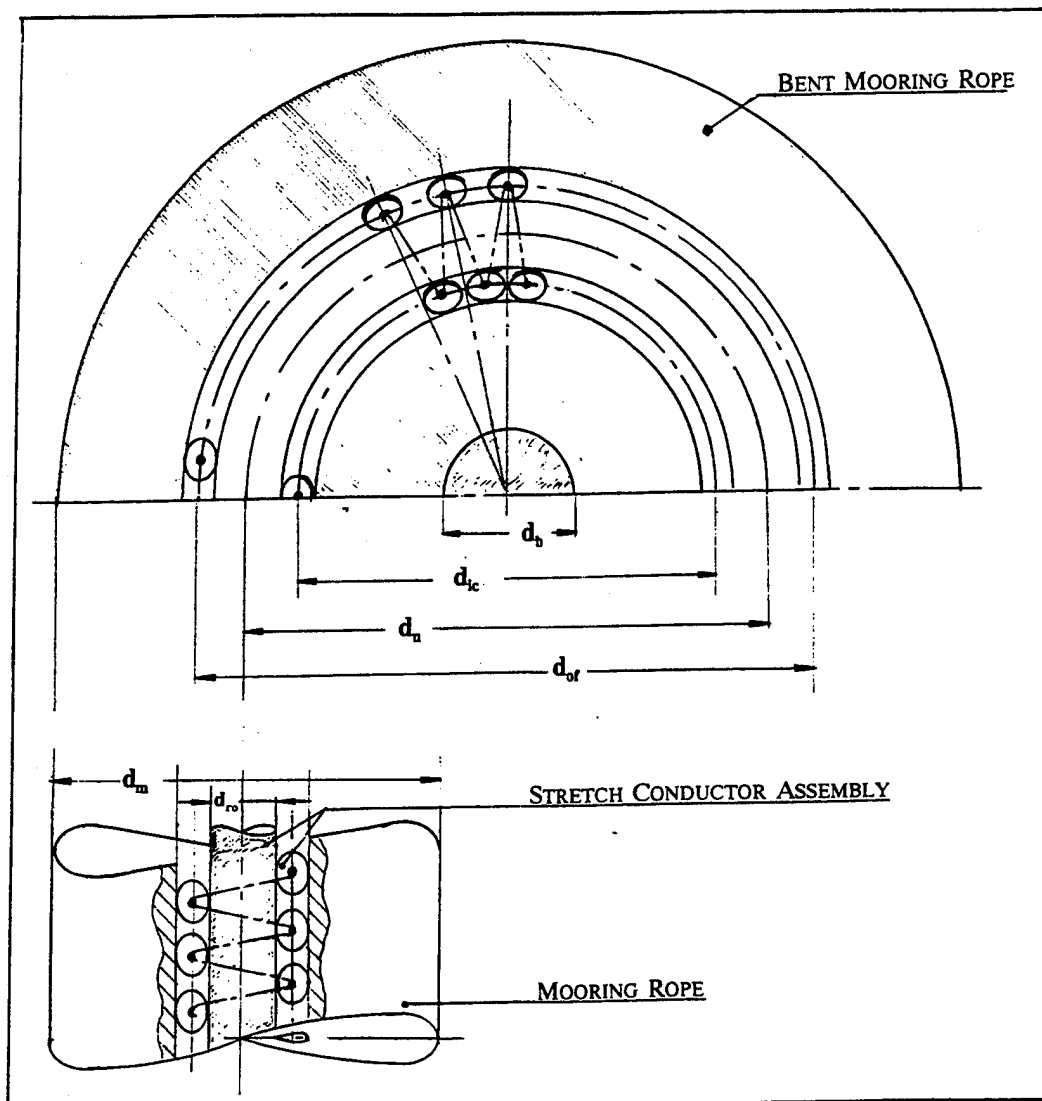


Figure 4: Rope with Conductor Assembly Core bent around Small Pin

We use the ratios $k = d_{co}/d_{ro}$ and $j = d_n/d_{ro}$ to determine the contraction ratio δ_{ic} of the inner conductor layer during bending. It is:

$$\delta_{ic} = d_{ic}/d_n = (d_n - d_{ro} - d_{co})/d_n = 1 - (1 - k)/j, \quad \delta_{ic} \leq 1.0 \quad (14)$$

Or the minimum pitch length $p_{o \min}$ and the value of the wrap angle $\cos \alpha_{o \max}$ is δ_{ic}^{-1} times the result determined with Eqn. (12) or (13). It is important to assure good flexibility of the conductor assembly so it will not be damaged when the covering rope bends in service.

3.0 PROTOTYPE STRETCH CONDUCTOR

3.1 Design

A first prototype conductor assembly was procured from a specialty cable producer (Cortland Cable). The cable core is a spliceable braid from a high stretching nylon fiber with an approximate strength of 500 lbs and an elongation at break of 33 percent. Around this core two insulated conductors of about #25AWG resistance with additional stretch capability were spiraled at a helix angle of ≈ 68 degrees. About 30 percent space between conductors is maintained with this arrangement resulting in a flexible, knotable design. The k value (conductor diameter/rope core diameter) for this construction is 0.26 or higher, the conservatively selected Poisson ratio μ is 0.3. A first attempt with a thinner fiber core (k value of 0.5) was not producible since the insulated conductors would not bend around the smaller core. The low Poisson ratio of 0.3 was chosen to reflect possible compression of the nylon cable core at its contact with the spiraled conductors. Poisson ratios for fiber ropes are at least 0.5 and can be 1.0 and larger for new ropes (2). Poisson ratio values for small textile braids should be smaller, but are difficult to measure. The conductor wrapping process was tried on two different twisting machines, only one machine was able to produce the assembly with a constant conductor twist. The assembly had to be exposed to a heat treatment to remove the elastic springiness of the polyethylene conductor insulation. The conductor deformed permanently from a circular to a flat elliptic cross section after being spiraled around the nylon center braid and heat treated. The conductor's low density polyethylene insulation was tube extruded around the conductor core. Insulation applied by tube extrusion does not surround the copper conductor tightly unlike pressure extrusion. No outer protective braid was applied over the conductor layer, in order to ease splicing and testing. The stretch conductor assembly is shown in Figure 5.

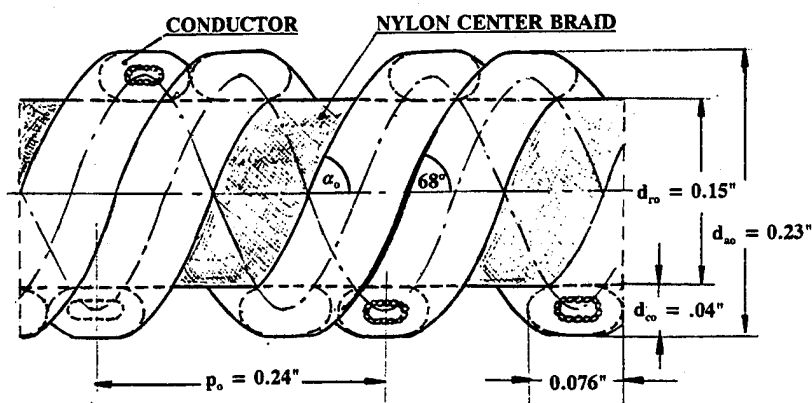


Figure 5 Side View of Stretch Conductor Assembly

3.2 First Test Results

A section of stretch conductor was terminated with eye-splices of the nylon center core to form a 50 inch long sample, see Figure 6. The conductors, first unwrapped and later reapplied over the nylon core in the splice zones, maintained their shape due to the heat treatment. This specimen was loaded in steps up to 300 lbs in WHOI's Baldwin tensile tester. The elongation was 23 percent at 300 lbs. At all load levels the conductor helixes could be moved, indicating that they were under no tension. The conductor resistance fluctuated within close margins over the entire test. This first test proved that the design can support 20 percent working stretch of a nylon rope. New tests are planned to higher stretch levels to determine the elongation limits of this design, and test its behavior under cyclic loading conditions.

3.3 Additional Steps to Complete the Stretch Conductor

Assuming successful test completion, as next step the coiled conductor geometry has to be frozen to prevent its distortion due to external local squeezing of a surrounding rope, which may lead to conductor failure. A protective jacket over the conductor layer is planned. This would be preferably in the form of a plastic extruded jacket, or an outer textile braid. Final step will be the overbraiding of the conductor assembly with a nylon strength member. The strength member will be designed as a braided sleeve to be in a tension jammed configuration when applied and tensioned over the stretch conductor assembly. Compressive forces of the tensioned nylon strength member on the coiled conductor assembly are minimized this way. With approximately 1 inch outer diameter a conductor rope with a strength of 20,000 to 25,000 lbs can be fabricated. Termination technique for such a rope has to assure that the conductors can exit the rope without being destroyed by shear action of the tensioned nylon strength member.

4.0 CONCLUSIONS

Calculations were developed which allow the specification of a conductor assembly design which can be subjected to a required working elongation - in this case 20 percent - without stretching the conductor itself. Conservative design values of k and μ were used to assure that the conductors will not elongate in use and be destroyed. A prototype conductor assembly has been designed and procured. Preliminary tensile tests demonstrated that the assembly can support at least 20 percent elongation without conductor stretch. Arresting the conductor geometry through an extruded jacket and covering of the assembly with a nylon braid to serve as a mooring rope with conductors will follow. Rope termination techniques have to assure that the conductors do not get squashed when exiting from the rope center at the end connection. A conductive lower rope for the ALTOMOOR mooring is the goal of this effort. Other applications would be in lift ropes or trigger lines with enclosed conductors. Such a conductor could also be embedded in the wall of a stretch hose. Regular embedded conductors failed in an ARPA supported stretch hose development in a cyclical flex tension fatigue test due to their inability to elongate sufficiently at the coupling interface with the hose (3).

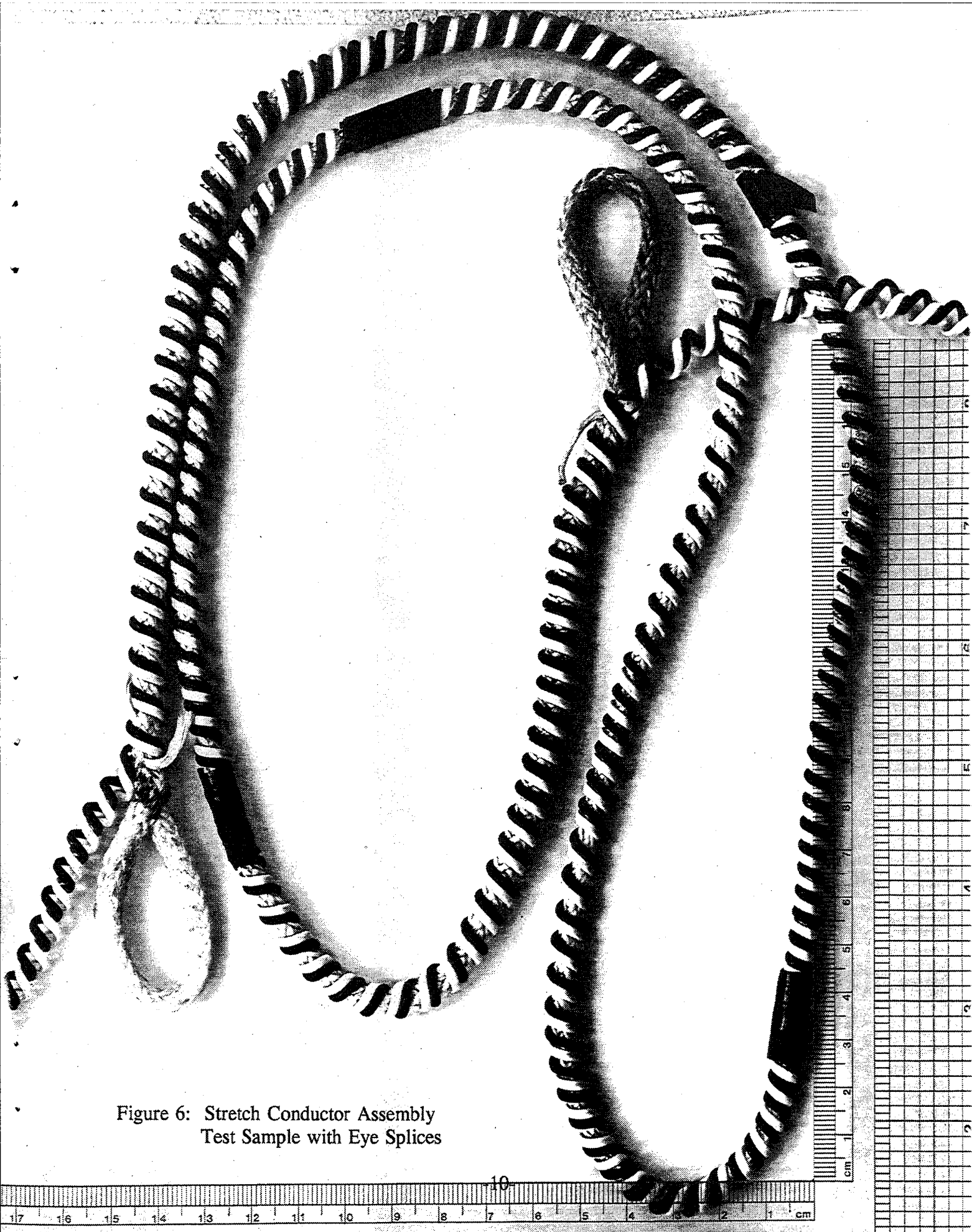


Figure 6: Stretch Conductor Assembly
Test Sample with Eye Splices

The calculation can be expanded to allow a defined amount of conductor stretch. This would allow to determine the amount of conductor elongation in a given cable design when the assembly is subjected to stretch. The effect of design changes on conductor stretch can be found this way and lead to a better understanding of the behavior of elongated conductor assemblies.

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- (2) Backer, S., Mandell, J.F., Williams, J.H.; *Deterioration of Synthetic Fiber Rope During Marine Usage*, Summary Progress Report R/T-11, Period January 1982 - June 1983, Fiber and Polymers Division, Massachusetts Institute of Technology, Cambridge, MA, Fig. 4.21, p.4.46.
- (3) Tests performed by Tension Member Technology for the SSAR/GAMOT program in 1994. The conductor failure occurred after 600 to 143,000 flex cycles with superimposed tension cycles. Failure identification from X-rays photos of hose length.

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16. Abstract (Limit: 200 words) A copper conductor formed into a helical configuration like a telephone cord can stretch by extending its geometry without elongating the conductor itself. This report establishes the proper configuration of copper conductors arranged in a helical pattern around a fiber core which can be used as center of a nylon rope with at least 20 percent working stretch. The calculation procedure allows the determination of the conductor's helix angle or pitch as function of the required assembly elongation, the cable assembly's geometry, and the fiber core's Poisson ratio. Limits of the geometry are established to assure defined flexibility of the cable assembly to allow bending of a surrounding fiber rope without conductor layer blockage. A sample stretch conductor assembly was procured and initial testing is described, proving the calculation method's ability to determine the correct geometry of the conductor assembly. Such conductor assemblies can be used as conductive core of nylon ropes suitable for coastal and deepsea buoy moorings or as lift or trigger lines for instrumentation. They are also considered the most suitable configuration which can endure the high stretch requirements of embedded conductors in a stretch hose wall at its transition into a coupling section.			
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